Dark Matter in Modern Cosmology

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Abstract. The presence of Dark Matter (DM) is required in the universe regulated by the standard general relativistic theory of gravitation. The nature of DM is however still elusive to any experimental search. We discuss here the process of accumulation of evidence for the presence of DM in the universe, the astrophysical probes for the leading DM scenarios that can be obtained through a multi-frequency analysis of cosmic structures on large scales, and the strategies related to the multi-messenger and multi-experiment astrophysical search for the nature of the DM.

DARK MATTER IN MODERN COSMOLOGY: GAINED EVIDENCE

There is overwhelming evidence that we live in a geometrically flat ($\Omega_0 \approx 1$) universe which is dominated - in the standard general relativistic cosmological paradigm - by a dark form of matter (Dark Matter - DM) and by an obscure form of energy (Dark Energy - DE). In such standard cosmological paradigm, DM provides a substantial fraction $\Omega_{DM} \approx 0.227$ of the overall matter-energy content (the rest being provided by Dark Energy with $\Omega_{DE} \approx 0.728$ with the baryonic contribution limited to $\Omega_b \approx 0.045$, see, e.g., Komatsu et al. 2010) and amounts to $\sim 83\%$ of the total mass content of the universe.
How did we arrive to such a conclusion? Is there a general and definite consensus on it?

The Dark Matter timeline

The discovery of the presence of DM can be considered as a typical scientific revolution (Kuhn, 1970) that induced a change in the reference (cosmological) paradigm. However, as often occurs in a paradigm shift, there was no single discovery, but new concepts were developed and integrated step-by-step [1].

To begin, there are actually two dark matter problems, the *local* Dark Matter close to the plane of our Galaxy, and the *global* Dark Matter surrounding galaxies, clusters of

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[1] In this context, it is necessary, since the beginning of this discussion, to acknowledge many reviews on the Dark Matter and related problems, as given by Faber & Gallagher (1979), Trimble (1987), Kormendy & Knapp (1987), Srednicki (1990), Turner (1991), Silk (1992), Ashman (1992), van den Bergh (2001), Ostriker & Steinhardt (2003), Rees (2003), Turner (2003), Colafrancesco (2006, 2007), Einasto (2004, 2009), among others.

galaxies and large scale structures.

The local Dark Matter (Oort 1932) in the Galactic disk is baryonic [faint stars or planet (jupiter)-like objects], since a collection of matter close to the galactic plane is possible if it has formed by the contraction of pre-stellar matter towards the plane accompanied by dissipation of the extra energy, so to conserve the flat shape of the population. It is now clear that the amount of local Dark Matter is low, and it depends on the mass boundary between luminous stars and faint invisible stars or planet-like objects (see Einasto 2009 for a discussion and references therein).

The global Dark Matter (to which we refer in this paper) is the dominating mass component in the universe; it is mainly concentrated in galaxies, clusters and superclusters of galaxies, and populates all other large-scale structures in the universe.

The first evidence for such global DM was obtained by F. Zwicky (1933). From observations of the radial velocities of eight galaxies in the Coma cluster, Zwicky found an unexpectedly large velocity dispersion $\sigma_v = 1019 \pm 360$ km s^{-1} [we note in passing that Zwicky's velocity dispersion from only eight galaxies agrees well with the modern value $\sigma_v = 1082$ km s^{-1}, as obtained by, e.g., Colless & Dunn (1996)]. Zwicky concluded from these observations that, for a velocity dispersion of ~ 1000 km s^{-1}, the mean density of the Coma cluster would have to be ~ 400 times greater than that which is derived from luminous matter. [2] Zwicky concluded, therefore, that in order to hold galaxies together in the cluster, the Coma cluster must contain huge amounts of some dark (i.e. not visible), cold matter (Zwicky used actually the words *"Dunkle Kalte Materie"* which might be regarded as the first reference to Cold Dark Matter ... even though not in the modern sense).

Not until three years later it was found (Smith 1936) that the Virgo cluster also appears to exhibit an unexpectedly high mass. Smith made the speculation that the excess mass of Virgo "*represents a great mass of internebular material within the cluster*" (see van den Bergh 2001).

Six years later than Zwicky's 1933 paper, Babcock (1939) obtained spectra of the Andromeda galaxy (M31) and found that in its outer regions the galaxy is rotating with an unexpectedly high velocity, far above the expected Keplerian velocity. He interpreted this result either as a high mass-to-light ratio in the periphery or as a strong dust absorption. Dark Matter in galaxies was also envisaged.

One year later, Oort (1940) studied the rotation and the surface brightness of the edge-on S0 galaxy NGC 3115. He found that *"The distribution of mass in this system appears to bear almost no relation to that of light."* He concluded that a value $M/L \sim 250$ should be present in the outer regions of NGC 3115 (note that this value is reduced by almost an order of magnitude if the modern distance to this galaxy is adopted). Oort ended his paper by writing that *"There cannot be any doubt that an extension of the measures of rotation to greater distances from the nucleus would be of exceptional interest."*

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[2] Zwicky actually overestimated the mass-to-light ratio of the Coma cluster because he assumed a Hubble parameter $H_0 = 558 kms^{-1} Mpc^{-1}$. His value for the overdensity of Coma should therefore be reduced from 400 to ~ 50 by using the actual value of the Hubble parameter. It is interesting to note that Hubble's prestige was so great at that time, that none of the early authors thought of reducing Hubble's constant as a way of lowering their mass-to-light ratios.

However, no connection was made between the missing mass in this S0 galaxy, and the Zwicky and Smith missing mass problem in clusters of galaxies.

The DM problem remained as a kind of "anomaly" for roughly a quarter of century after the initial Zwicky's paper until when Kahn & Woltjer (1959) pointed out that M31 and our Galaxy were moving towards each other, so that they must have completed most of a (very elongated) orbit around each other in a Hubble time. These authors found that if M31 and our Galaxy started to move apart ~ 15 Gyr ago, the mass of the Local Group had to be $\gtrsim 1.8 \times 10^{12} M_\odot$. Assuming that the combined mass of the Andromeda galaxy and the Milky Way system was $0.5 \times 10^{12} M_\odot$, Kahn & Woltjer (1959) concluded that most of the mass of the Local Group existed in some invisible form. They opined that it was most likely that this missing mass was in the form of hot (with temperature of $\sim 5 \times 10^5$ K) gas. From a historical perspective, it is interesting to note that also Kahn & Woltjer did not seem to have been aware of the earlier papers by Zwicky (1933) and Smith (1936) on the missing mass problem in clusters of galaxies.

In the 1960's and 1970's, Babcock's optical rotation curve of M31, and that of Rubin & Ford (1970), were extended to even larger radii by Roberts & Whitehurst (1975) using 21-cm line observations that reached a radial distance of ~ 30 kpc. These observations clearly showed that the rotation curve of M31 did not exhibit any Keplerian drop-off. From these observations Roberts & Whitehurst (1975) concluded that the mass-to-light ratio had to be $\gtrsim 200$ in the outermost regions of M31. Again, it is interesting to note that neither Babcock, nor Roberts & Whitehurst, cited the 1933 paper by Zwicky. In other words, no connection was made between the missing mass in the outer region of spiral galaxies and the missing mass in galaxy clusters such as Coma (Zwicky 1933) and Virgo (Smith 1936). Regarding the flat outer rotation curves of galaxies Roberts (1999, as quoted in van den Bergh 2001) recalls that this result *"was, at best, received with skepticism in many colloquia and meeting presentations."* Nonetheless, the paper by Roberts & Whitehurst (1975) was important because it, together with papers on the stability of galactic disks (e.g. Ostriker & Peebles 1973), and on the apparent increase of galaxy mass with increasing radius (e.g. Ostriker, Peebles & Yahil 1973), first convinced the majority of astronomers that a missing mass problem existed.

By the mid of 1970's enough research was done for the community to see that the missing mass "anomaly" was not going to go away, and the majority of astronomers had become convinced that missing mass existed in cosmologically significant amounts. *"When... an anomaly comes to seem more than just another puzzle of normal science, the transition to crisis and to extraordinary science has begun"* (Kuhn 1970). In other words, it began to be clear in the mid 1970's that a paradigm shift would be required to interpret the observations that seemed to support the ubiquitousness of missing (dark) matter in the universe.

At the beginning of the 1980's the presence of DM was directly confirmed by many independent sources: the dynamics of galaxies and of stars within galaxies (Rubin et al. 1978, 1980), the mass determinations of galaxy clusters based on gravitational lensing [3] (see, e.g., Bartelmann & Schneider 2001 for a review and references therein), X-ray

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[3] It is noted, in passing, that Zwicky (1937) also pointed out that gravitational lensing might provide useful information on the total masses of galaxies.

studies of clusters of galaxies (see, e.g., Forman et al. 1985), the indications of the first N-body simulations of large scale structure formation and of galaxies and cluster formation (see, e.g., White et al. 1987).

At this time it was also already clear that structures in the universe form by gravitational clustering, started from initially small fluctuations of the density of matter (Peebles 1980). In order to form the presently observed structures, the amplitude of the density fluctuations must be at least one thousandth of the density itself at the epoch of recombination, when the universe started to be transparent. The relic emission coming from this epoch was first detected in 1965 (Penzias & Wilson 1965) as an (almost) isotropic cosmic microwave background (CMB). When finally the fluctuations (anisotropies) of the CMB were measured by the COBE satellite, first an large angular scales (Smooth et al. 1992), and by the Boomerang experiment, also on smaller angular scales (de Bernardis et al. 2000), they appeared to be two orders of magnitude lower than expected from the density evolution of the luminous (baryonic) mass. The solution of the problem was suggested independently by several theorists. If we suppose that the dominating mass component of the universe - Dark Matter - is not made of ordinary matter but of some sort of non-baryonic matter, then density fluctuations can start to grow much earlier, and have at the time of recombination the amplitudes needed to form the structures observed today. The interaction of this non-baryonic matter with radiation is much weaker than that of ordinary matter, and radiation pressure does not slow the early growth of fluctuations.

However, beyond the indubitable success of the DM-dominated cosmological framework, the fundamental uncertainty on the DM nature remained.

The first suggestion for a non-baryonic DM was made referring to particles well known at that time to physicists, i.e. neutrinos (ν) (see, e.g., Pontecorvo 1967), for which "theoretical and practical considerations" push progressively some physicists to agree on a non zero mass neutrino (Quantum mechanics allow then the oscillation of neutrinos: a ν_e can, along its travel in the universe, become a ν_μ and vice-versa). This can be considered as the first input from particle physics to the search for the nature of DM. Rees (1977) was one of the first astrophysicists to tackle with the idea of non-baryonic nature for the cosmologically relevant DM, and suggested that: *"There are other possibilities of more exotic character - for instance the idea of neutrinos with small ($\sim$ few eV) rest mass has been taken surprisingly seriously by some authors"*. However, this scenario of hot DM soon led to major problems, because neutrinos move with very high velocities which prevents the formation of small structures as galaxies (Silk 1968).

Thus some other hypothetical non-baryonic particles were suggested, such as axions (Abbott & Sikivie 1983, Preskill, Wise & Wilczek, 1983; Dine & Fischler, 1983) or Weakly Interacting Massive Particles (e.g. WIMPs, Goldberg 1983, Ellis et al. 1983). The essential character of these particles to make them good for cosmology is that they have much lower velocities than neutrinos. Because of this, the new version of Dark Matter scenario was called Cold, in contrast to neutrino-dominated Hot Dark Matter scenario.

Numerical simulations of the evolution of the structure of the universe confirmed the formation of filamentary superclusters and voids in the Cold Dark Matter scenario of structure formation (e.g. Ostriker 1993 and references therein). The suggestion of the Cold Dark Matter has solved most problems of the new cosmological paradigm.

One unsolved problem remained. Estimates of the total matter density (ordinary plus DM) yield values $\Omega_m \sim 0.27$ of the critical density. This value - not far from unity, but definitely smaller than unity - is neither favoured by theory nor by the data, including the measurements of the cosmic microwave background, the galaxy dynamics and the expansion rate of the universe obtained from the study of distant type Ia supernovae (SNe). To fill the matter/energy density gap between unity and the observed matter density it was assumed that some sort of Dark Energy (DE) exists. [4] By the early 2000's, refined CMB anisotropy experiments (e.g., Boomerang, Maxima, DASI, and then WMAP) demonstrated that the CMB anisotropy spectrum is the largest detector for the presence of Dark Matter in their fluctuation spectrum, and by combining their measurements with independent cosmological distance measurement using type Ia SNe (Perlmutter 2000), a first determination of the overall matter-energy composition of the universe was possible (see Komatsu et al. 2010 for a recent determination of the cosmological parameter set). The inclusion of the DE term in the general relativistic cosmological scenario has filled the last gap in the modern cosmological paradigm.

False alarms and diversionary manoeuvres

No good detective story is complete without at least one false clue or some diversionary manoeuvres.

Oort (1960, 1965) believed that he had found some dynamical evidence for the presence of missing mass in the disk of the Galaxy. If true, this would have indicated that some of the dark matter was dissipative in nature. However, late in his life, Jan Oort confessed (as reported by van den Bergh 2001) that the existence of missing mass in the Galactic plane was never one of his most firmly held scientific beliefs. Detailed observations, that have been reviewed by Tinney (1999), show that brown dwarfs cannot make a significant contribution to the density of the Galactic disk near the Sun.

The presence of large amounts of matter of unknown origin has given rise to speculations on the validity of the Newton law of gravity at very large distances. One of such attempts is the Modified Newton Dynamics (MOND) model, suggested by Milgrom (1983) and Milgrom & Bekenstein (1987) (see, e.g., Sanders 1990 for a discussion). Indeed, MOND is able to explain spiral galaxies quite well imposing a minimum acceleration scale $a_0 \sim cH_0$, without assuming the presence of some hidden matter. If the MOND scale a_0 is allowed to run, galaxy clusters might be explained as well. However, there exist several arguments which make this model unrealistic (see Einasto 2009 for a discussion). In addition, a full relativistic theory is needed in any case to construct a consistent cosmology. A tensor-vector-scalar theory (TeVeS, see Bekenstein 2004) has been then proposed and it is successful in reproducing MOND in the proper limit even for photons, and respecting also the classical tests of general relativity (GR). Whether a consistent cosmology can be constructed with this theory remains to be seen (in fact, both MOND and TEVES models are not covariant formalisms of a general

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[4] This assumption was not new: already Einstein added to his cosmological equations a cosmological constant term Λ (corresponding to a vacuum energy).

relativistic theory of gravitation, see Capozziello et al. 2008).

Extended Gravity scenarios have been therefore suggested to explain the large-scale cosmological problem of the accelerated expansion of the universe and have been also worked out to describe the morphology and dynamics of very peculiar systems, like the bullet cluster (Brownstein & Moffat 2007). Such a scenario is today the best alternative to a pure particle DM scenario.

The Astro-Particle connection

All the available information indicates that the standard scenario for structure formation in the GR framework requires that the global Cold Dark Matter must be non-baryonic, its density fluctuations start to grow much earlier than perturbations in the baryonic matter, and have at the recombination epoch large enough amplitudes to form all structures seen in the universe.

However, the actual nature of the CDM particles still remains unknown. Physicists have attempted to discover particles which have the properties needed to explain the structure of the universe, but so far without success. This means that a true Astro-Particle connection should be developed in the search for the nature of DM. In conclusion, even though the direct information on the dark components of the universe (DM and DE) comes solely from astronomical observations, it is clear that a definite understanding of the nature of DM will come through the discovery and the multi-messenger study of the fundamental particles of which DM consists of.

A last remark

The discovery of DM has the general character of a typical scientific revolution connected with changes of paradigms, as discussed by Kuhn (1970) in his book "The Structure of Scientific Revolutions". There are not so many areas in modern astronomy and cosmology where the development of ideas can be described in these terms.

DARK MATTER IN MODERN COSMOLOGY: THE PRESENT

Motivations

All the reliable indications for the presence of the dark components of the universe, and especially of DM, come solely from astronomical evidence.

The main indications are: i) galaxy rotation curves; ii) dwarf galaxy mass estimators; iii) galaxy cluster mass estimators; iv) lensing reconstruction of the gravitational potential of galaxy clusters and large scale structures; v) the combination of global geometrical probes of the universe (e.g., CMB) and distance measurements (e.g., SNe).

Supporting evidence comes also form Large Scale Structure simulations for the leading structure formation scenario.

Dark Matter candidates

There are five basic properties that DM candidates must have: DM must be dissipationless, collisionless, cold, must behave like a fluid on galactic scales and above, must behave sufficiently classically to be confined on galactic scales (see Baltz 2004). The first three properties do not place any stringent constraint on the space of possibilities, while the last two place upper and lower (loose) bounds, respectively, on the mass of the particle. Such wide space of possibilities allowed theoreticians to propose many candidates for the DM particles (see Feng 2010). Among these, the most viable and widely considered candidates for the DM are, so far, neutralinos (the lightest particles of the minimal supersymmetric extension of the Standard Model, MSSM, see e.g. Jungman et al. 1996), sterile neutrinos (the lightest right-handed neutrino, see e.g. Shaposhnikov 2007) or even other forms of light DM (see e.g. Boyanovsky et al.2007).

In the following, and for the sake of brevity, we will focus mainly on the astrophysical probes related to some of these DM candidates, specifically neutralinos and sterile neutrinos. We will also focus our discussion, for the sake of conciseness, on the best astrophysical laboratories for DM indirect search: i) galaxy clusters (the largest bound containers of DM in the universe) and ii) dwarf spheroidal galaxies (the cleanest, nearby and bound DM halos).

Dark Matter Probes

Direct detection of DM particles is the cleanest and most decisive discriminant (see, e.g., Munoz 2003 for a review). However, it would be especially interesting if astronomical techniques were to reveal some of the fundamental particle properties predicted by fundamental theories.

The dark side of the universe sends us, in fact, signals of the presence and of the nature of DM that can be recorded using different astrophysical probes. These probes are of *inference* and *physical* character.

Inference probes [i.e., the CMB anisotropy spectrum (see, e.g., Hu & Dodelson 2002, Spergel et al. 2003, Komatsu et al. 2010), the dynamics of galaxies (Zwicky 1933), the hydrodynamics of the hot intra-cluster gas (see Sarazin 1988, Arnaud 2005 for a review) and the gravitational lensing distortion of background galaxies by the intervening potential wells of galaxy clusters (see Bartelmann & Schneider 1999 for a review and references therein)] tell us about the presence, the total amount and the spatial distribution of DM in the large scale structures of the universe but cannot provide detailed information on the nature of DM.

Physical probes tell us about the nature and the physical properties of the DM particles and can be obtained by studying the astrophysical signals of their annihilation/decay in the atmospheres of DM-dominated structures (like galaxy cluster and galaxies). These probes can be recorded over a wide range of frequencies from radio to gamma-rays and prelude to a full multi-frequency, multi-experiment and multi-messenger search for the nature of DM in cosmic structures.

A test case: neutralino DM

Among the viable competitors for having a cosmologically relevant DM species, the leading candidate is the lightest particle of the minimal supersymmetric extension of the Standard Model (MSSM, see Jungman et al. 1996), plausibly the neutralino χ, with a mass M_χ in the range between a few GeV to a several hundreds of GeV (see Baltz 2004 for a review). Information on the nature and physical properties of the neutralino DM can be obtained by studying the astrophysical signals of their interaction/annihilation in the halos of cosmic structures (galaxy clusters and/or galaxies). These signals [5] involve, in the case of a χ DM, emission of gamma-rays, neutrinos, together with the synchrotron and bremsstrahlung radiation and the Inverse Compton Scattering (ICS) of the CMB (and other background) photons by the secondary electrons produced in the DM annihilation process (see Fig.1).
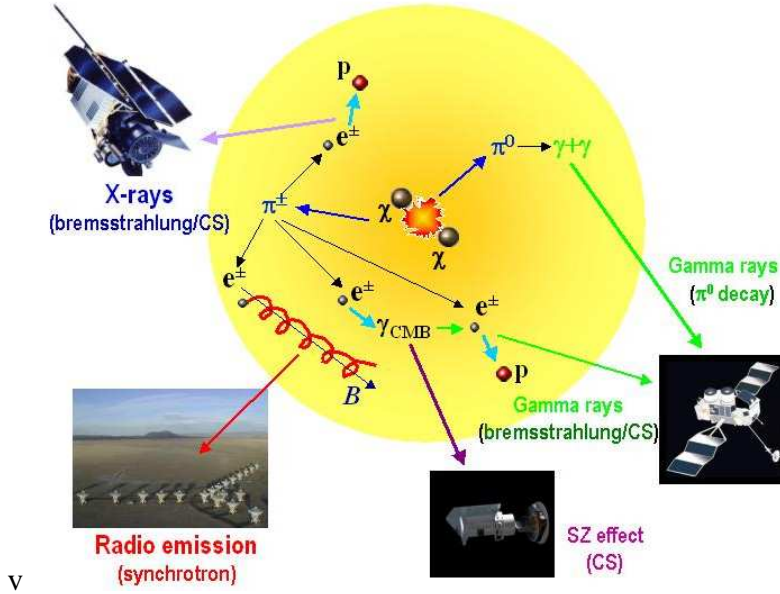

FIGURE 1. A simple model which shows the basic astrophysical mechanisms underlying the search for the nature of χ DM particles through the emission features occurring in large-scale structures (e.g., galaxy clusters and galaxies). These mechanisms are, among others: γ-ray emission from $\pi^0 \to \gamma + \gamma$, relativistic bremsstrahlung of secondary $e^\pm$ and Inverse Compton Scattering (ICS) of CMB photons by secondary $e^\pm$; X-ray/UV emission due to non-thermal bremsstrahlung and ICS of background photons by secondary $e^\pm$; synchrotron emission by secondary $e^\pm$ diffusing in the intra-cluster magnetic field; Sunyaev-Zel'dovich (SZ$_{DM}$) effect (i.e. ICS of CMB photons by secondary $e^\pm$)

The χ annihilation rate is $R = n_\chi(r)\langle\sigma v\rangle$, where $n_\chi(r) = n_{\chi,0}g(r)$ is the neutralino number density with radial distribution given by the function $g(r)$, and $\langle\sigma v\rangle$ is the $\chi\chi$ annihilation cross section averaged over a thermal velocity distribution at freeze-out

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[5] Neutralino DM annihilation produces several types of particle and anti-particle fluxes, whose complete description is not discussed here for the sake of brevity. We refer the interested reader to Colafrancesco, Profumo & Ullio (2006) for the case of galaxy clusters and Colafrancesco, Profumo & Ullio (2007) for the case of dwarf galaxies.

temperature (Jungman et al. 1996). The range of neutralino masses and pair annihilation cross sections in the most general supersymmetric DM setup is extremely wide. Neutralinos as light as few GeV (see Bottino et al. 2003), and as heavy as hundreds of TeV (see Profumo 2005) can account for the observed CDM density through thermal production mechanisms, and essentially no constraints apply in the case of non-thermally produced neutralinos. Turning to the viable range of neutralino pair annihilation cross sections, coannihilation processes do not allow to set any lower bound, while on purely theoretical grounds a general upper limit on $\langle \sigma v \rangle \lesssim 10^{-22}(M_\chi/\text{TeV})^{-2}\text{cm}^3/\text{s}$ can be set (Profumo 2005). The only general argument which ties the relic abundance of a neutralino (WIMP) with its pair annihilation cross section is given by

$$\Omega_{DM} h^2 \simeq (3 \times 10^{-27}\text{cm}^3/\text{s})/\langle \sigma v \rangle \tag{1}$$

(see Jungman et al. 1996). This relation can be, however, badly violated in the general MSSM, or even within minimal setups, such as the minimal supergravity scenario (see discussion in Colafrancesco, Profumo & Ullio 2006).

Neutralino annihilations in DM halos

Neutralinos which annihilate inside a DM halo produce quarks, leptons, vector bosons and Higgs bosons, depending on their mass and physical composition. Electrons and positrons (hereafter refereed to as electrons for simplicity) are then produced from the decay of the final heavy fermions and bosons. The different composition of the $\chi\chi$ annihilation final state will in general affect the form of the electron spectrum.

Neutral pions produced in $\chi\chi$ annihilation decay rapidly in $\pi^0 \to \gamma\gamma$ and generate most of the continuum spectrum at energies $E \gtrsim 1$ GeV.

Secondary electrons are produced through various prompt generation mechanisms and by the decay of charged pions, $\pi^\pm \to \mu^\pm \nu_\mu(\bar{\nu}_\mu)$, with $\mu^\pm \to e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$ and produce $e^\pm$, muons and neutrinos.

Secondary electrons are subject to spatial diffusion and energy losses. Both spatial diffusion and energy losses contribute to determine the evolution of the source spectrum into the equilibrium spectrum of these particles, i.e. the quantity which is used to determine the multi-frequency spectral energy distribution (SED) induced by DM annihilation. The time evolution of the secondary electron spectrum is described by the transport equation:

$$\frac{\partial n_e}{\partial t} = \nabla\left[D\nabla n_e\right] + \frac{\partial}{\partial E}\left[b_e(E)n_e\right] + Q_e(E,r) , \tag{2}$$

where $Q_e(E,r)$ is the $e^\pm$ source spectrum, $n_e(E,r)$ is the $e^\pm$ equilibrium spectrum and b_e (given here in units of GeV/s) is the $e^\pm$ energy loss per unit time $b_e = b_{ICS} + b_{synch} + b_{brem} + b_{Coul}$, with $b_{ICS} \approx 2.5 \cdot 10^{-17}(E/GeV)^2$, $b_{synch} \approx 2.54 \cdot 10^{-18}B_\mu^2(E/GeV)^2$, $b_{brem} \approx 1.51 \cdot 10^{-16}(n_{th}/cm^{-3})\left(\log(\Gamma/n_{th})+0.36\right)$, $b_{Coul} \approx 7 \cdot 10^{-16}(n_{th}/cm^{-3})\left(1+\log(\Gamma/n_{th})/75\right)$. Here n_{th} is the ambient gas density and $\Gamma \equiv E/m_e c^2$.

The DM source spectrum, $Q_e(E,r)$, is constant over time, and under the assumption that

the population of high-energy $e^{\pm}$ can be described by a quasi-stationary ($\partial n_e/\partial t \approx 0$) transport equation, the secondary electron spectrum $n_e(E,r)$ reaches its equilibrium configuration mainly due to synchrotron and ICS losses at energies $E \gtrsim 150$ MeV and to Coulomb losses at smaller energies.

The diffusion coefficient D in eq.(2) sets the amount of spatial diffusion for the secondary electrons: it turns out that diffusion can be neglected in galaxy clusters while it is relevant on galactic and sub-galactic scales (see discussion in Colafrancesco, Profumo & Ullio 2006, 2007).

To get a more physical insight on the relevance of spatial diffusion in large-scale structures, it is useful to consider the following qualitative solution for the average electron density

$$\frac{dn_e(E,r)}{dE} \approx [Q_e(E,r)\tau_{loss}] \times \frac{V_s}{V_s+V_o} \times \frac{\tau_D}{\tau_D+\tau_{loss}} \tag{3}$$

(see Colafrancesco 2005, Colafrancesco et al. 2006) which resumes the relevant features of the transport equation (eq. 2). Here, $V_s \propto R_h^3$ and $V_o \propto \lambda^3(E)$ are the volumes occupied by the DM source and the one occupied by the diffusing electrons which travel a distance $\lambda(E) \approx [D(E) \cdot \tau_{loss}(E)]^{1/2}$ before loosing much of their initial energy. The relevant time scales in eq. (2) are the diffusion time-scale, $\tau_D \approx R_h^2/D(E)$, and the energy loss time-scale $\tau_{loss} = E/b_e(E)$, where we assume the generic scaling of the diffusion coefficient $D(E) = \tilde{D}_0(E/E_0)^\gamma B^{-\gamma}$.

For $E > E_* = (\tilde{D}_0 E_0/R_h^2 b_0 B_\mu^\gamma)^{1/(1-\gamma)}$ [for simplicity we kept leading terms only, implementing $b(E) \simeq b_0(B_\mu)(E/GeV)^2 + b_{Coul}$], the condition $\tau_D > \tau_{loss}$ (and consistently $\lambda(E) < R_h$) holds, the diffusion is not relevant and the solution of eq. (2) is $dn_e/dE \sim Q_e(E,r)\tau_{loss}$ and shows an energy spectrum $\sim Q(E) \cdot E^{-1}$. This situation ($\lambda(E) < R_h$, $\tau_D > \tau_{loss}$) applies to the regime of galaxy clusters, i.e. structures on $\sim$ Mpc scales (see Colafrancesco et al. 2006).

For $E < E_*$, the condition $\tau_D < \tau_{loss}$ (and consistently $\lambda(E) > R_h$) holds, the diffusion is relevant and the solution of Eq. (2) is $dn_e/dE \sim [Q_e(E,r)\tau_D] \times (V_s/V_o)$ and shows an energy spectrum $\sim Q(E) \cdot E^{(2-5\gamma)/2}$ which is flatter or equal to the previous case for reasonable values $\gamma = 1/3 - 1$. This last situation ($\lambda(E) > R_h$, $\tau_D < \tau_{loss}$) applies to the regime of dwarf galaxies, i.e. structures on $\sim$ kpc scales (see Colafrancesco 2005, Colafrancesco et al. 2007).

Secondary electrons eventually produce radiation by synchrotron in the magnetized atmosphere of cosmic structures, bremsstrahlung with ambient protons and ions, and Inverse Compton Scattering (ICS) of CMB (and other background) photons (and hence an SZ effect, Colafrancesco 2004). These secondary particles also produce heating of the ambient gas by Coulomb collisions with the ambient plasma particles.

Spectral Energy Distribution from DM annihilation

The astrophysical signals of neutralino DM annihilation computed in various DM models can be visible over the entire e.m. spectrum, from radio to γ-ray frequencies (see Figs.2 and 3). As pointed by Colafrancesco et al. (2006), the relevant physical properties which determine the features of the emitted radiation are the composition

of the neutralino, its mass, and the value of the annihilation cross section. We consider here, for the sake of illustration, a few representative DM models with low (40 GeV), intermediate (81 GeV) and high (100 GeV) neutralino mass.

Gamma rays. Gamma-ray emission is predominantly due to the hadronization of the decay products of $\chi\chi$ annihilation with a continuum γ-ray spectrum due to the decay $\pi^0 \to \gamma + \gamma$ (see, e.g., Colafrancesco & Mele 2001, Colafrancesco et al. 2006), even though the direct neutralino annihilation results in a line emission at an energy $\sim M_\chi$.
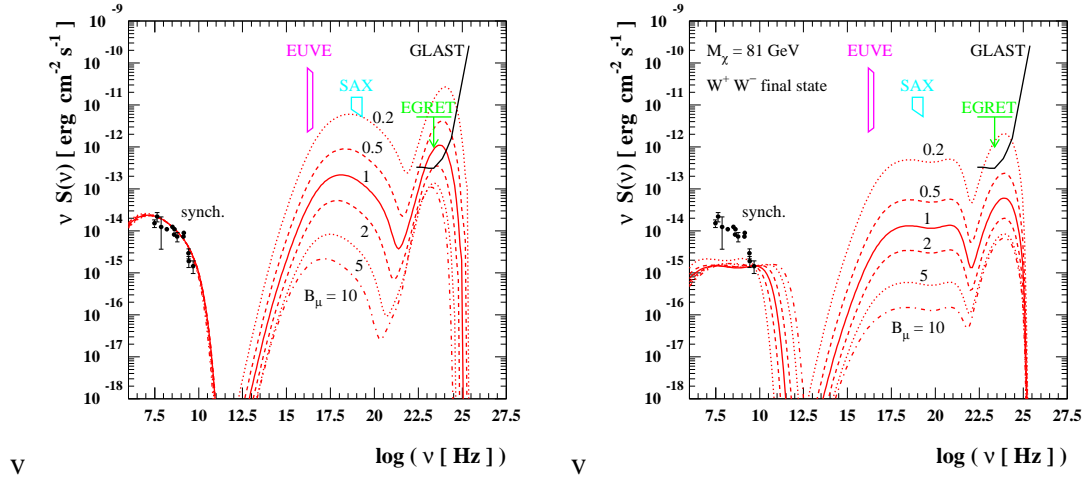

FIGURE 2. Multi-frequency SED of the Coma cluster for two representative DM models: $M_\chi = 40$ GeV ($b\bar{b}$; left) and $M_\chi = 81$ GeV (W^+W^-; right). The halo profile is a NFW profile with $M_{vir} = 0.9\,10^{15}M_\odot h^{-1}$ and $c_{vir} = 10$, with DM subhalo setup as given in Colafrancesco et al. (2006). The scaling of the multi-frequency SED with the value for the mean magnetic field B_μ in Coma is shown for the two DM models. The neutralino pair annihilation rate has been tuned to fit the radio halo data Figures from Colafrancesco et al. (2006).

Gamma-ray emission is also expected from secondary $e^\pm$ through bremsstrahlung and ICS of CMB photons up to high energies (see Figs.2, 3).
For the case of the Coma cluster, the gamma-ray flux produced by the low mass model ($M_\chi = 40$ GeV, $b\bar{b}$) is dominated by the continuum $\pi^0 \to \gamma\gamma$ component and it is a factor ~ 5 lower than the EGRET upper limit of Coma at its peak frequency once the annihilation cross section is normalized to fit the radio halo data (see Fig. 2, left panel). Such gamma-ray flux could be, nonetheless, detectable by the Fermi (GLAST)–LAT experiment for low values of the magnetic field $\lesssim 0.5\,\mu$G. A DM model with intermediate mass ($M_\chi = 40$ GeV, $W^\pm$) predicts lower gamma-ray flux below the EGRET limit but still detectable by Fermi (GLAST)-LAT only for very low values of the magnetic field $\lesssim 0.2\,\mu$G (Fig 2, right panel).
The rather low neutralino masses of these models make them difficult to be testable by Cherenkov gamma-ray detectors operating at high threshold energies.
For the case of smaller cosmic structures, like the Draco dwarf galaxy, a DM model with $M_\chi = 100$ GeV (normalized to the EGRET upper limit for Draco) predicts that the dominant gamma-ray emission is still given by the continuum $\pi^0 \to \gamma\gamma$ component

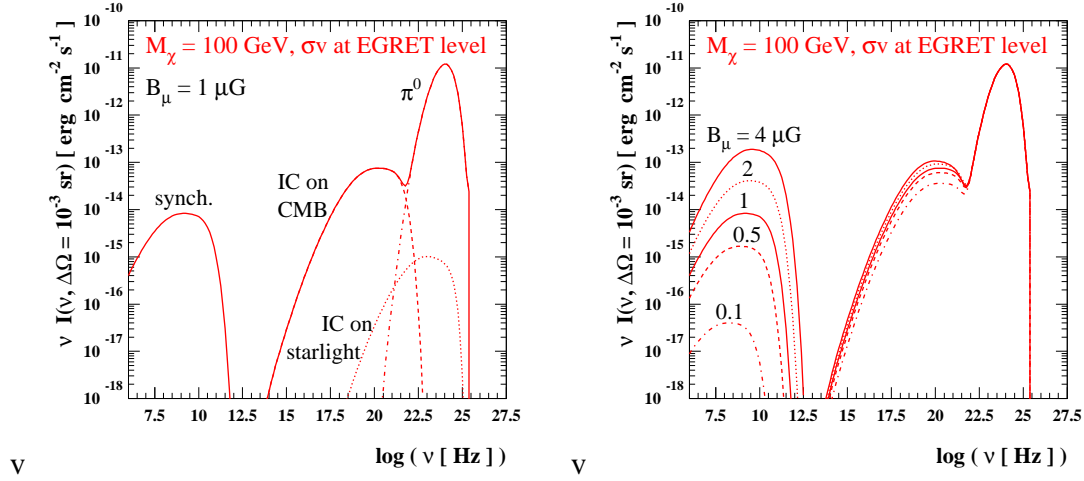**FIGURE 3.** Multi-frequency SED of Draco for a 100 GeV neutralino annihilating into $b\bar{b}$ and for a magnetic field of $1\mu G$ (left). The effect of varying the magnetic field strength is also shown (right). The neutralino pair annihilation rate has been tuned to give a gamma-ray signal at the level of the EGRET upper limit. Figures from Colafrancesco et al. (2007).

while the dominant ICS emission (i.e., ICS on CMB photons) is a factor $\sim 10^2$ less intense, a fact mainly due to diffusion effects. The other ICS component considered for Draco (i.e., ICS on starlight photons) peaks at frequencies comparable with those of the $\pi^0 \to \gamma\gamma$ component, but is negligible being a factor $\sim 10^4$ less intense (see Fig. 3). Also this model with $M_\chi = 100$ GeV is difficult to be tested by Cherenkov experiments.

Radio emission. Secondary $e^\pm$ produced by $\chi\chi$ annihilation can generate synchrotron emission in the magnetized atmosphere of galaxy clusters (as well as galaxies) which could be observed at radio frequencies as a diffuse radio emission (i.e. a radio halo or haze) centered on the DM halo. Observations of cluster radio-halos are, in principle, very effective in constraining the neutralino mass and composition (Colafrancesco & Mele 2001, Colafrancesco et al. 2006), under the hypothesis that DM annihilation provides a major contribution to the radio-halo flux. Under this hypothesis, a pure energy requirement requires that the neutralino mass is bound to be $M_\chi \geq 23.4 \text{GeV}(v/GHz)^{1/2}(B/\mu G)^{-1/2}$ in order that the secondary $e^\pm$ emit at frequencies $v \geq 1$ GHz, as observed in cluster radio halos (see Fig.2). A soft DM model ($b\bar{b}$ with $M_\chi = 40$ GeV) is able to reproduce both the overall radio-halo spectrum of Coma and the spatial distribution of its surface brightness (see Fig.4), while a hard DM model (W^+W^- with $M_\chi = 81$ GeV) is excluded being its radio spectrum too flat to reproduce the Coma data.

For the case of dwarf galaxies (e.g. Draco), radio emission is strongly affected by
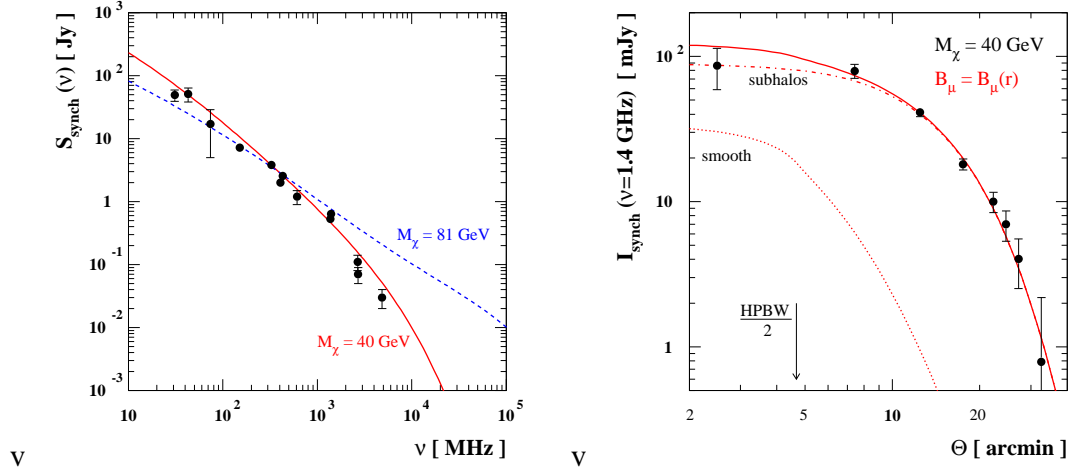
FIGURE 4. **Left**. The radio flux density spectrum of Coma in two DM models: soft spectrum due to a $b\bar{b}$ annihilation final state (solid line) with $M_\chi = 40$ GeV) and hard spectrum due to a W^+W^- channel (dashed line) with $M_\chi = 81$ GeV. **Right**. Surface brightness distribution of Coma at $\nu = 1.4$ GHz, within a beam equal to $9\rlap{.}'35$ (HPBW), for the the soft neutralino model (solid). We consider a magnetic field $B(r) = B_0(1 + (r/r_{c1})^2) \cdot [1 + (r/r_{c2})^2]^{-\beta}$ with $B_0 = 0.55$ μG, $\beta = 2.7$, $r_{c1} = 3'$ $r_{c2} = 17\rlap{.}'5$. The contributions to the radio brightness from the smooth DM halo component only (dotted) and from subhalos only (dashed) are also displayed (see Colafrancesco et al. 2006 for details).

propagation effects. [6] Fig.5 shows that for a propagation set up (set up #1) with a Kolmogorov spectrum ($D \propto E^{1/3}B_\mu^{-1/3}$) there is a depletion of the electron populations with a significant fraction leaving the diffusion region, while for a propagation set up (set up #2) with a steeper spectrum ($D \propto E^{0.6}B_\mu^{-0.6}$) they are more efficiently confined within the diffusion region but still significantly misplaced with respect to the emission region. As a consequence, also the spectral shape of the radio flux of Draco is affected by diffusion effects which produce a steeper spectral slope when the electron populations are more efficiently confined within the diffusion region (i.e. propagation set up #2) with respect to the case (i.e. propagation set up #1) where there is a depletion of the electron populations with a significant fraction leaving the diffusion region (see Colafrancesco et al. 2007 for details).

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[6] For the diffusion coefficient we consider here the case of a Kolmogorov form $D(E) = D_0/B_\mu^{1/3} (E/1 \text{ GeV})^{1/3}$, with $D_0 = 3 \cdot 10^{28}$ cm^2 s^{-1}, in analogy with its value for the Milky Way (here B_μ is the magnetic field in units of μG). The dimension of the diffusion zone is, consistently with the Milky Way picture, about twice the radial size of the luminous component, i.e. ≈ 102 arcmin for Draco (set #1 of propagation parameters). An extreme diffusion model in which the diffusion coefficient is decreased by two orders of magnitudes down to $D_0 = 3 \cdot 10^{26}$ cm^2 s^{-1} (implying a much smaller scale of uniformity for the magnetic field), and with a steeper scaling in energy, $D(E) = D_0 (E/1 \text{ GeV})^{-0.6}$ (this is the form sometime assumed for the Milky Way) is considered for comparison (we label this propagation parameter configuration set #2)
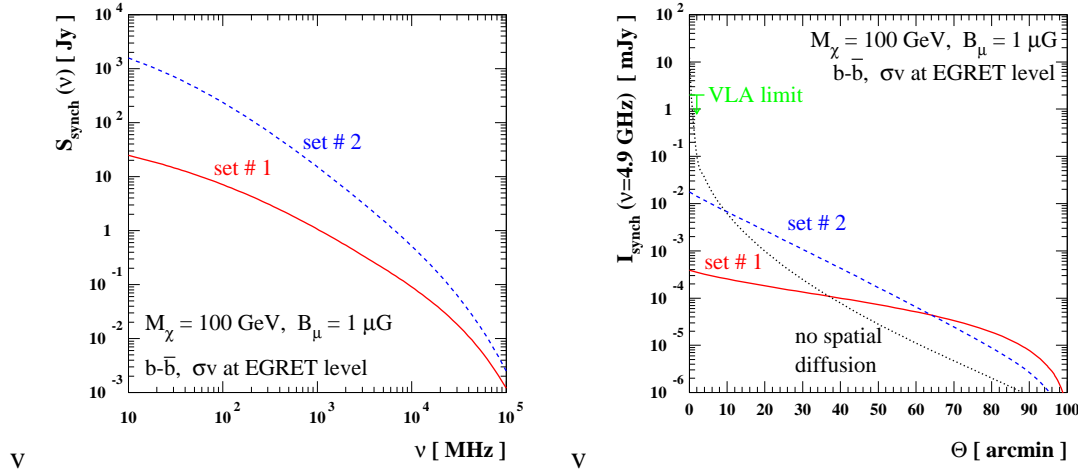
FIGURE 5. Radio flux density spectrum (left) and surface brightness distribution (right) of Draco at $\nu = 4.9$ GHz for a sample χ model with $M_\chi = 100$ GeV annihilating into $b\bar{b}$ with a cross section tuned as to give 2 events in the EGRET experiment. Results are shown for the two choices of propagation parameters, as labelled; the case when spatial diffusion is neglected is also shown for comparison in the right panel (dotted curve). Surface brightness radial profiles are plotted for a 3 arcsec angular acceptance, corresponding to the VLA resolution used to search for a point-like radio source at the center of Draco (the VLA upper limit is also plotted in the figure).

ICS of CMB: from microwaves to gamma-rays Secondary $e^\pm$ produced by neutralino annihilation up-scatter CMB (and other background) photons that will redistribute over a wide frequency range up to gamma-ray frequencies. A soft neutralino model with $M_\chi = 40$ GeV and $\langle \sigma v \rangle = 4.7 \cdot 10^{-25} cm^3 s^{-1}$, with $B_\mu = 1.2$ yields EUV and HXR fluxes which are more than one order of magnitude fainter than the Coma data (see Fig.2). Increasing M_χ does not provide a decent fit of the radio-halo spectrum (see Fig. 2, right panel) and yields, in addition, extremely faint EUV, HXR and gamma-ray fluxes, which turn out to be undetectable even by Fermi (GLAST) and/or by the next coming high-energy experiments. Increasing $\langle \sigma v \rangle$ by a factor $\sim 10^2$ (i.e., up to values $\langle \sigma v \rangle \approx 7 \cdot 10^{-23} cm^3 s^{-1}$) can fit the EUV and HXR data on Coma but the relative $\pi^0 \to \gamma\gamma$ gamma-ray flux exceeds the EGRET upper limit on Coma.
Lowering the magnetic fields down to values $\sim 0.15 \mu G$ can fit both the HXR and the EUV fluxes of Coma but also in this case the $\pi^0 \to \gamma\gamma$ gamma-ray flux predicted by the same model exceeds the EGRET limit on Coma, rendering untenable also this alternative. Actually, the EGRET upper limit on Coma set a strong constraint on the combination of values B and $\langle \sigma v \rangle$ so that magnetic field larger than $\gtrsim 0.3 \mu G$ are required for the parameter setup of the $b\bar{b}$ model with $M_\chi = 40$ GeV (Fig.22 of Colafrancesco et al. (2006) shows the upper limits on the value of $\langle \sigma v \rangle$ as a function of the assumed value of the mean magnetic field of Coma).
According to these results, it is impossible to fit all the available data on Coma for a consistent choice of the DM model and of the cluster magnetic field (see also discussion in Colafrancesco et al. 2010).

For the Draco dwarf galaxy the dominant ICS on CMB component produces fluxes of X-rays at the level of $\sim 10^{-15} - 10^{-14}$ erg cm^{-2} s^{-1} when the gamma-ray flux is normalized to the EGRET upper limit. The constraints obtainable by Fermi (GLAST) observation of Draco will hence set much more realistic expectations for the diffuse X-ray emission produced from DM annihilation in Draco which could eventually be tested with high sensitivity X-ray, and especially HXR and soft γ-ray observations where this ICS spectrum peaks at $E \sim 100$ keV.

ICS of CMB: SZ effect from DM annihilation. Secondary e$^{\pm}$ produced by neutralino annihilation interact with the CMB photons and up-scatter them to higher frequencies producing a peculiar SZ effect (as originally realized by Colafrancesco 2004) with specific spectral and spatial features. The DM induced spectral distortion writes as

$$\Delta I_{\mathrm{DM}}(x) = 2\frac{(k_{\mathrm{B}}T_0)^3}{(hc)^2}y_{\mathrm{DM}}\,\tilde{g}(x) \, , \tag{4}$$

where T_0 is the CMB temperature and the Comptonization parameter is

$$y_{\mathrm{DM}} = \frac{\sigma_T}{m_e c^2}\int P_{\mathrm{DM}}d\ell \, , \tag{5}$$

in terms of the pressure P_{DM} contributed by the secondary $e^{\pm}$. The function $\tilde{g}(x)$, with $x \equiv h\nu/k_{\mathrm{B}}T_0$, for the DM produced secondary $e^{\pm}$ can be written as

$$\tilde{g}(x) = \frac{m_e c^2}{\langle\varepsilon\rangle}\left\{\frac{1}{\tau_{DM}}\left[\int_{-\infty}^{+\infty} i_0(xe^{-s})P(s)ds - i_0(x)\right]\right\} \tag{6}$$

in terms of the secondary $e^{\pm}$ optical depth $\tau_{DM} = \sigma_T \int d\ell n_e$ (with n_e given by the solution of eq.2), of the photon redistribution function $P(s) = \int dp f_{\mathrm{e}}(p)P_{\mathrm{s}}(s;p)$ with $s = \ln(\nu'/\nu)$, in terms of the photon frequency increase factor ν'/ν, of the $e^{\pm}$ momentum (p) distribution $f_{\mathrm{e}}(p)$, of $i_0(x) = 2(k_{\mathrm{B}}T_0)^3/(hc)^2 \cdot x^3/(e^x - 1)$, and of the quantity

$$\langle\varepsilon\rangle \equiv \frac{\sigma_{\mathrm{T}}}{\tau_{DM}}\int Pd\ell = \frac{\int Pd\ell}{\int n_e d\ell} = \int_0^{\infty} dp f_{\mathrm{e}}(p)\frac{1}{3}pv(p)m_e c \tag{7}$$

which is the average energy of the secondary electron population (see Colafrancesco 2004). Fig.6 shows the maps of the CMB temperature change,

$$\frac{\Delta T}{T_0} = \frac{(e^x - 1)^2}{x^4 e^x}\frac{\Delta I}{I_0} \, , \tag{8}$$

at 223 GHz as produced by the SZ$_{DM}$ effect in the neutralino models with mass of 40 GeV ($b\bar{b}$) and 81 GeV ($W^{\pm}$), compared to the temperature change due to the residual thermal SZ effect produced by the intracluster gas of the bullet cluster. The spatial separation between the DM and thermal SZE of this cluster is due to the fact that the SZ$_{DM}$ effect has a very different spectral shape with respect to the thermal SZ effect: it yields a temperature decrement at all the microwave frequencies $\lesssim 600$ GHz,
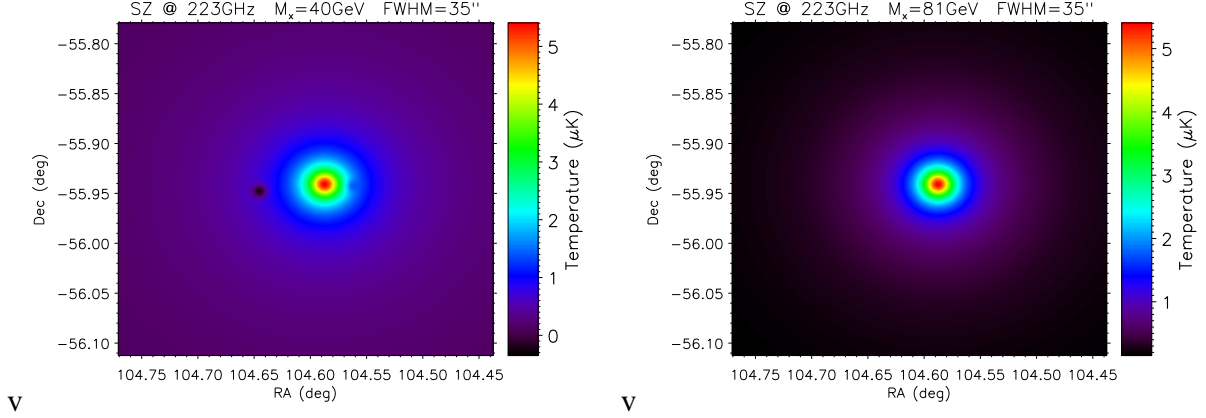
FIGURE 6. The simulated SZ maps of the cluster 1ES0657-556 observable at $\nu = 223$ GHz with a telescope of angular resolution similar to SPT (see Colafrancesco et al. 2007 for details) for a neutralino mass $M_\chi = 40$ GeV, $b\bar{b}$ (left panel) and $M_\chi = 81$ GeV $W^\pm$ (right panel) with the DM density model setup of Colafrancesco et al. (2006).

where the thermal SZ effect is predominantly observed, and produces a temperature increase only at very high frequencies > 600 GHz. This behavior is produced by the large frequency shift of CMB photons induced by the ICS off the relativistic secondary electrons generated by the neutralino annihilation. As a consequence, the zero of the SZ_{DM} effect is effectively removed from the microwave range and shifted to a quite high frequency ~ 600 GHz with respect to the zero of the thermal SZ effect, a result which allows, in principle, to estimate directly the pressure of the two electron populations and hence to derive constraints on the neutralino DM model (see Colafrancesco 2004).

It is, however, necessary to stress that in such frequency range there are other possible contributions to the overall SZ effect, like the kinematic SZ effect and other non-thermal SZ effects which could provide additional biases.

We stress that a SZ_{DM} effect is expected in every neutralino DM halo and its amplitude depends basically on the optical depth of the DM-produced secondary electrons, and hence on the detailed distribution of the equilibrium spectrum of the secondary electrons. The SZ_{DM} effect produced in a dwarf galaxy, like Draco (see, e.g., Colafrancesco 2004, Culverhouse, Ewans and Colafrancesco 2006), is however quite low when the spatial diffusion of secondary electrons is efficiently operating: we find, in fact, that the SZ signal towards the center of Draco is negligible even when we normalize the gamma-ray signal at the level of the EGRET upper limit.

Heating. Low energy secondary electrons produced by neutralino annihilation heat the intra-cluster gas by Coulomb collisions since the Coulomb loss term dominates the energy losses at $E \lesssim 150$ MeV. The DM-induced heating rate at the center of galaxy clusters is usually higher than the intra-cluster gas cooling rate for steep DM density profiles (like the NFW one). The radius of the region in which such steep DM density profile produce an excess heating increases with increasing neutralino mass, once the DM-produced SED are normalized to fit the radio halo data. The heating effect provides, hence, strong constraint to the annihilation cross-section for neutralino DM models. In

order to have the DM-induced heating rate lower than the bremsstrahlung cooling rate at the cluster center the annihilation cross section must be reduced by a large factor (see Colafrancesco et al. 2010 for a discussion in the case of Coma cluster). Cored DM density profiles alleviate the over-heating problem for neutralino DM models by reducing the electron equilibrium spectrum $n_e(E,r)$ in the cluster central region. This makes DM models more consistent with the cluster heating rate constraints for low (a few to ~ 10 GeV) and intermediate ($\sim 40-60$ GeV) neutralino mass, but not for high neutralino mass (~ 500 GeV or more) that still produce excess heating (see Colafrancesco et al. 2010).

Multi-Messengers. Stronger constraints to DM annihilation models can be set by a multi-messenger analysis of DM signals. Such multi-messenger constraints include, e.g., observations and limits on positrons, antiprotons, radio and γ-rays from the Galactic Centre region and the optical depth of CMB photons (see discussion in Colafrancesco et al. 2010); multi-frequency (radio, microwave, X-ray and gamma-ray) observations from satellites of the MW, external galaxies (like M31, e.g. Borriello et al. 2009) and cosmic background radiation, in addition to those obtained from dwarf galaxies and galaxy clusters (see Colafrancesco 2006, Profumo & Ullio 2010 for reviews).
We stress that these multi-messenger bounds are quite robust and not easily avoidable, and therefore they set further constraints to any specific multi-frequency analysis of DM models, as we have described in this review.

Cosmic rays from neutralino annihilation
Neutralino annihilation in nearby DM clumps (like e.g. the Galactic center or galactic DM satellites) produces cosmic rays that diffuse away and can be directly recorded by cosmic rays experiments.
Some of the cosmic ray observations (at energy between 10 GeV and a few TeV) obtained with PAMELA (Adriani et al. 2009), ATIC (Chang et al. 2008), Fermi (Abdo et al. 2009), and HESS (Aharonian et al. 2009) show a positron excesses over background expectations (Strong et al. 2009).
An attractive and widely explored possibility is that the observed positron excesses are produced by neutralino (WIMP) DM annihilation, even though these excesses have rather plausible astrophysical explanations (see, e.g., Hooper et al. 2009, Yuksel et al. 2009, Profumo 2008, Dado & Dar 2009, Biermann et al. 2009, Katz et al. 2009). However, if the neutralino annihilation cross section is of the order of thermally-averaged annihilation cross section at freeze out, i.e. $\langle \sigma v \rangle \approx 3 \times 10^{-26} cm^3/s$, the resulting annihilation signal is far too small to explain the observed cosmic ray excesses.
A seemingly attractive solution is to postulate that DM interacts with a light force carrier ϕ with fine structure constant $\alpha_X \equiv \lambda^2/(4\pi)$ (see, e.g., Cirelli et al. 2009). This effectively enhances the annihilation cross section by a quite large factor $S = \frac{\pi \alpha_X/v_{rel}}{1-exp(-\pi \alpha_X/v_{rel})}$ (usually referred to as Sommerfeld enhancement, see e.g. Arkani-Hamed et al. 2009), where v_{rel} is the DM particle relative velocity. Since the required DM mass to explain the positron observations is $\sim$ TeV, the required m_ϕ is $\sim$ GeV, values $S \sim 10^3$ can be obtained, assuming $\langle \sigma v_{rel} \rangle \approx \langle \sigma v \rangle$, that can fit the positron excess. The Sommerfeld enhancement therefore provides an elegant mechanism for boosting neutralino DM an-

nihilations now.

Of course, for a viable solution, DM must not only annihilate with the correct rate, but it must also be produced with the right density and form all large-scale structure in agreement with observations. However, Feng et al. (2009) have shown that the required enhancement implies thermal relic densities that are too small to be all of DM. In addition, upper bounds on possible Sommerfeld enhancements can be derived from the observation of elliptical galactic dark matter halos (like the case of NGC270), and these bounds also (generically) seem to exclude enhancements that can explain the observed positron excesses (see discussion by Feng et al. 2009).
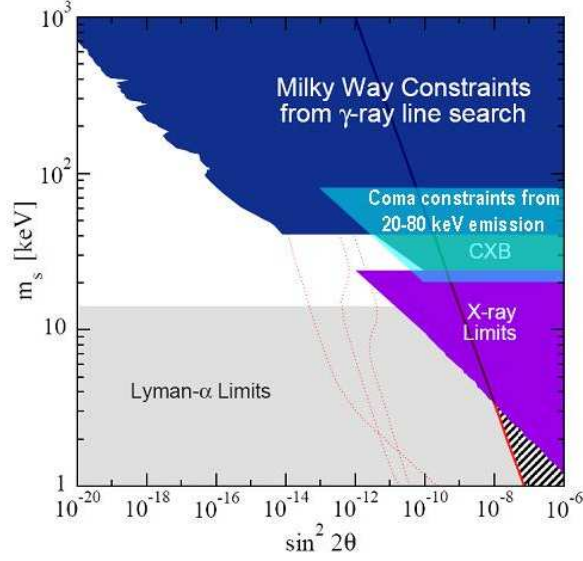
Other DM scenarios

Recent progress has greatly expanded the list of well-motivated candidates and the possible signatures of DM (see Feng 2010 for a recent review). Beyond any attempt to be exhaustive and/or complete in this respect, we briefly discuss here the interesting case of a light DM candidate, i.e. sterile neutrinos.

Sterile neutrinos may be produced in a number of ways and their relic density depends on the sterile neutrino mass and mixing angle, but all of the mechanisms require small masses m_s and mixing angles θ for sterile neutrinos to be a viable DM candidate. As for the astrophysical (indirect detection) search, it is interesting to notice that the radiative decay of sterile neutrinos, $\nu_s \rightarrow \nu_i + \gamma$ (where ν_i indicate the standard low-mass neutrinos), produces a narrow line emission whose energy provides information on the sterile neutrino mass m_s. Therefore, X-ray spectral observations from galaxy clusters are a powerful tool to set contraints on sterile neutrinos in the plane $m_s - sin^2(2\theta)$. The available constraints on sterile neutrinos from X-ray spectra of galaxy clusters, combined with those obtained from the Cosmic X-ray Background, Lyα limits and gamma-ray line limits from the MW are shown in Fig.7. The constraints from Coma observations in the 20-80 keV band are shown by the cyan dashed area. The possible interpretation of the intensity excess in the 8.7 keV line (at the energy of the FeXXVI Ly-γ line) in the spectrum of the Galactic center observed by the Suzaku X-ray mission in terms of decay of a sterile neutrino with mass of 17.4 keV and value of the mixing angle $sin^2(2\theta) = (4.1 \pm 2.2) \cdot 10^{-12}$ (see Prokhorov & Silk 2010), lies in the allowed region of mass–mixing angle for DM sterile neutrino shown is Fig.7.

This figure shows that models with lower mixing angles θ and neutrino masses m_s up to a few hundreds keV or even $\gtrsim$ MeV are still available. In this case, next generation high-sensitivity hard X-ray detectors like NuSTAR and/or NeXT, or next coming soft gamma-ray experiments will be able to set relevant constraints to this light DM model.

DARK MATTER IN MODERN COSMOLOGY: THE FUTURE

All solid evidence for DM is gravitational, and there is also strong evidence against DM having strong or electromagnetic interactions. However, direct and indirect probes for DM have, so far, not yet given a definite (positive) answer. In addition, some of the puzzling anomalies (e.g., DAMA, PAMELA) are not easy to explain within canonical

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FIGURE 7. The sterile neutrino mass m_s and mixing $sin^2(2\theta)$ parameter space, where the shaded regions are excluded. The strongest direct bounds are shown, labeled as Milky Way (Yuksel et al. 2008), Cosmic X-ray Background (Boyarsky et al. 2006), and X-ray limits (summarized by Watson et al. 2006). The strongest indirect bounds (Seljak et al. 2005), Viel et al. 2006) are shown by the grey horizontal band. The excluded Dodelson-Widrow model (Dodelson & Widrow 1994) is shown by the solid line; rightward, the DM density is too high (stripes). The dotted lines indicate example models (see Abazajian & Fuller 2002), now truncated by the available constraints. The cyan shaded area indicates our constraints from the HXR (soft gamma-ray) limit on Coma (Colafrancesco 2008). Figure from Colafrancesco (2008) adapted from the original one by Yuksel et al. (2008).

WIMP DM models (see Feng 2009 for a discussion). This experimental frustration and theoretical embarassement have motivated the search for new DM candidates. Among the logical alternatives to the WIMP paradigm (i.e., the fact that particle physics theories designed to explain the origin of the weak scale often naturally contain particles with the right relic density to be DM), then, one of the most widely explored ones is provided by hidden DM, that is, DM that has no standard model gauge interactions (see Feng 2009, 2010 for reviews).

At the moment, therefore, the DM search is continuing to be a great challenge. The direction in this effort are: direct search experiments, indirect probes of DM signals coming from cosmic sources, indirect indications on the nature of DM coming from laboratory experiments, like the LHC experiment. The next future is certainly bright in this context and expectations are rather high.

In the cosmological and astrophysical context, the refinement for the indirect DM search calls for a Multi[3] approach in the optimal astrophysical laboratories: i) multi-frequency to probe the consistency of DM annihilation/decay signals across the e.m. spectrum; ii) multi-messenger to cross-check the possible e.m. signals in cosmic structures at different scales; iii) multi-experiment to determine the robustness of the DM signals with different experimental techniques.

Multi^3 DM search: optimal astrophysical laboratories

The analysis of the spatial and spectral intensity of the astrophysical signals coming from neutralino annihilation is a powerful tool to unveil the elusive nature of DM. However, the DM-induced signals are expected to be confused or even overcome by other astrophysical signals originating from the ambient gas and/or from the relativistic plasmas present in the atmospheres of galaxy clusters and galaxies, especially when all these components are co-spatially distributed with the DM component.

An ideal system to detect DM annihilation signals would be a system which is either devoid of diffuse emitting material (this is the case of dark galaxies, like many dwarf spheroidals) or a system with a clear spatial separation between the various matter components (this is, indeed, the case of the cluster 1ES0657-556 where the spatial distribution of DM which is clearly offset with respect to that of the intracluster gas).

A *multi-frequency* analysis greatly helps to disentangle DM signals in these optimal laboratories from signals of different astrophysical origin.

In the *multi-messenger* analysis previously evoked, dark (dwarf) galaxies are among the best sites for the astrophysical search for the nature of DM but the relative multi-frequency SED are usually quite dim. Definite probes of DM signals in such systems have to be then complemented with probes coming from other DM halos like galaxy clusters (on larger scales) and the center of the Galaxy (on closer scales).

The *multi-experiment* strategy combining radio and gamma-ray observations of dwarf galaxies, like Draco, obtainable with high sensitivity instruments (SKA, LOFAR, EVLA, Fermi) could set strong constraints on the nature of the DM particles see Colafrancesco et al. 2007 for a discussion). Fig.8 shows the limits in the $M_\chi - \langle \sigma v \rangle$ plane set from a Multi^3 analysis of neutralino annihilation signals (taking into account the Draco dwarf galaxy and some of the signals coming from the Milky Way) where the most constraining frequency ranges are, in fact, the radio and the gamma-ray bands.

As for galaxy clusters, a Multi^3 approach indicates that in the case of 1ES0657-556 the expected gamma-ray emission associated to the DM clumps is too low ($\lesssim 1$ count vs. ~ 10 background counts at $E > 1$ GeV) and cannot be resolved by Fermi from other possible sources of gamma-ray emission, both from the cluster 1ES0657-556 and from AGNs (or other γ-ray emitting galaxies) in the field. Radio telescopes have, in principle, excellent resolution and sensitivity to probe the different spectra and brightness distribution of the DM-induced synchrotron emission, but the theoretical uncertainties associated to the radio emission from the DM clumps in 1ES0657-556 render the interpretation of the expected signals quite uncertain: we evaluated (Colafrancesco et al. 2007) that the DM induced synchrotron emission from the largest DM clump is $\sim 3 - 10$ mJy (for a smooth or smooth plus 50% mass clumpiness NFW DM profile, soft DM model with $M_\chi = 40$ GeV with a $B = 1$ μG) at $\nu = 100$ MHz, still marginally detectable by LOFAR. In such a context, the possible detection of the SZ$_{DM}$ effect from this system, with the next generation high-sensitivity and high-resolution experiments, will provide an important complementary, and maybe unique, probe of the nature of DM.
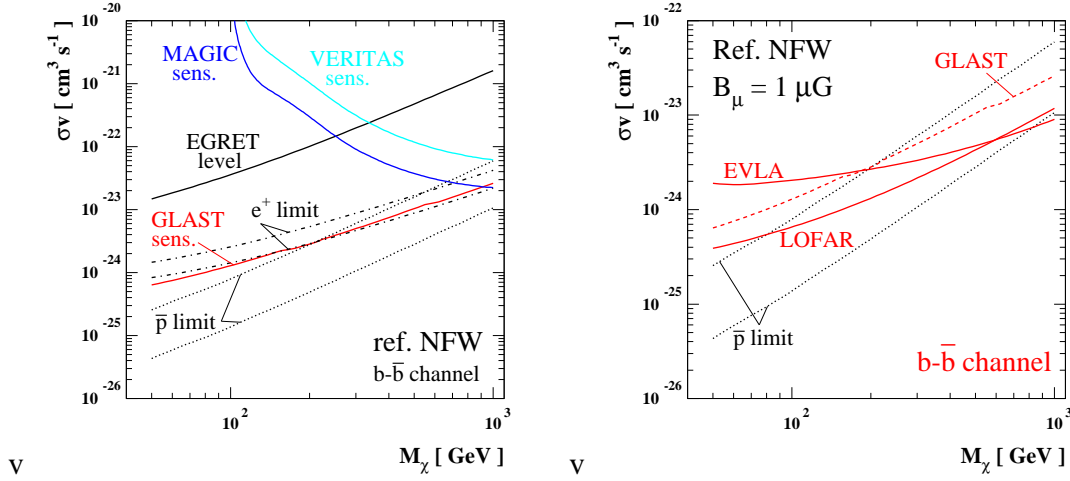
FIGURE 8. The limits in the $M_\chi - \langle\sigma v\rangle$ plane set by current and future gamma-ray experiments in a Multi[3] analysis of a $b\bar{b}$ neutralino annihilation model. **Left**. The solid black line indicates values of $\langle\sigma v\rangle$ required for a gamma-ray flux of the Draco dwarf galaxy matching the 2 events in EGRET between 1 and 10 GeV, for exposures and angular cuts as specified in the data analysis, assuming a reference NFW halo model. The black dotted and dot-dashed curves show the limits from the flux of, respectively, antiprotons and positrons in the Milky Way halo (the two lines corresponding to two different cosmic ray propagation setups); The solid red, dark blue and light blue curves indicate the projected sensitivity of Fermi (GLAST), MAGIC and VERITAS for Draco. **Right**. The projected sensitivity of future diffuse radio source searches from the direction of Draco. For comparison, we also indicate the sensitivity of gamma-ray search experiments, and the constraints from the antiproton and positron flux (the two lines corresponding to two different propagation setups for the Milky Way). (Figures and details from Colafrancesco et al. 2007).

DM or modified gravity?

The DM particle solution of the global DM problem is not univocally accepted. A different, more radical approach to explain the cosmological DM problem can be taken if one notes that the evidence for missing mass arises because of a mismatch between the gravitational field one would predict from the observed mass distribution in the universe and the observed gravitational field. The observed discrepancies arise when the effective gravitational acceleration is around, or below, the value $a_0 \sim 10^{-7} cms^{-2}$, that is in a regime of very weak gravitational field (see Ferreira & Starkman 2009 for a discussion). The point where modified gravity scenarios are at stake, is that the Newtonian theory of gravity - and general relativity - break down in this regime (see Fig. 9).

It has been shown that modified theory of gravity that incorporates quantum effects can explain a crucial set of puzzling astronomical observations (galaxy flat rotation curves, galaxy cluster structure and the accelerated expansion of the universe), including the "wayward" motion of the Pioneer spacecraft in our solar system (e.g. Moffat 2005, 2006; see also Brownstein & Moffat 2006a,b,c).
Beyond the details of the specific approaches to a modified or extended theory of gravity that have been presented so far, it is important to notice that a relativistic theory of
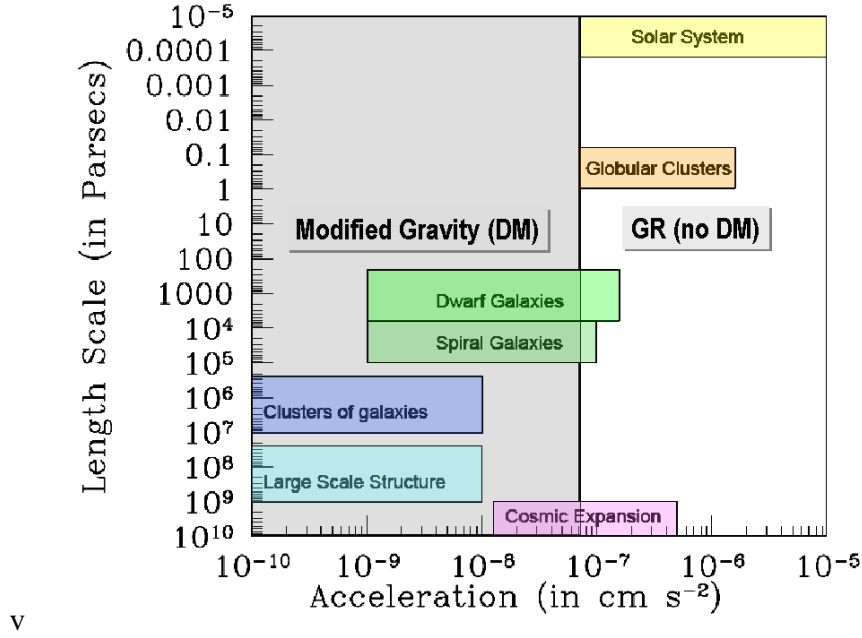
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FIGURE 9. Evidence for deviations from general relativity (GR) or evidence for the presence of Dark Matter (DM) tend to appear in systems in which the acceleration scale is weak (the left side, gray shaded part of the plot) at $\lesssim 7 \times 10^{-8} cms^{-2}$. There is strong evidence for either of the above in dwarf galaxies, spiral galaxies, galaxy clusters, large scale structures and in the expansion of the universe itself. Figure adapted from the original one by Ferreira & Starkman (2009).

modified gravity allows to make a number of specific predictions on a wide range of scales, from the scales of compact objects such as stars or black holes (in the limit of strong gravitational field), to the scales of formed structures on large scales (such as galaxies and galaxy clusters) up to the very large-scale structure scales and the largest scale probed by CMB anisotropies (in the limit of weak gravitational field) (see, e.g., Ferreira & Starkman 2009, Capozziello et al. 2009, Capozziello & Francaviglia 2008, Schmidt et al. 2009, among others).

It is, therefore, conceivable to use the next coming experimental probes on both strong gravitational fields (in the vicinity of very compact objects) and weak gravitational field (on large-scale cosmic structures) to set relevant constraints on the level and on the spatial scales at which the modification of the relativistic theory of gravity could occur.

EPILOGUE

Viable DM models which are consistent with WMAP limits on Ω_{DM} and Ω_{DE} and with the structure and evolution of galaxy clusters are able to produce substantial astrophysical signals especially detectable at radio, microwave, X-ray and gamma-ray frequencies. The constraints that the multi-frequency observations of the optimal astrophysical laboratories for DM search can set on the $\langle \sigma v \rangle$-M_χ plane, combined with the WMAP (relic abundance) constraints on $\langle \sigma v \rangle$, are able to efficiently restrict the available neu-

tralino DM models. Additional restrictions of this plane may be obtained through a multi-messenger approach by comparing the previous astrophysical constraints to the constraints coming from both accelerator physics and from other cosmological probes (e.g., the study of the emission features from the galactic center region, galactic satellites, dwarf galaxies, external galaxies) which are sensitive to the amount and nature of the DM. Direct DM detection experiments have already explored large regions of the most optimistic SUSY models, and the planned next-generation experiments will probably be able to explore also the core of the SUSY models. In this context, the astrophysical study of DM annihilation proves to be complementary, and hardly competitive, especially when a full multi-messenger and multi-experiment approach is chosen.

When combined with future accelerator results, such Multi[3] (multi-frequency, multi-messenger, multi-experiment) astrophysical search might greatly help us to unveil the elusive nature of Dark Matter.

The extended theory of gravity, on both an empirical and theoretical level, seems to be the most viable alternative to a dark cosmological model in which Dark Matter will remain still elusive to laboratory and astrophysical probes.

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